Easy Evaluation of Streamer Discharge Criteria

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Abstract: An easily implemented method is devised, where analytical criteria for the occurrence of streamer discharges in strong electric fields are evaluated. This is highly useful when designing high voltage power transmission systems and components where the insulation is provided by a gas, e.g. air or SF_6.

Keywords: High voltage, Electric field, Streamer, Breakdown, Flashover.

1. Introduction

In recent development of efficient power transmission systems two important trends influencing the engineering efforts are: (i) The steadily increasing voltage levels introduced to reduce resistive losses and (ii) Compacting, i.e. trying to make the equipment as small as possible. From an insulation point of view, however, these two requirements are conflicting in the sense that making clearance distances between conductors at different voltage levels smaller, while at the same time also increasing these voltage differences, obviously makes the occurrence of electric discharges and flashovers, see Fig. 1, more probable. Avoiding this to happen clearly requires a very thorough design work; critical areas suffering from excessive stress must be identified followed by appropriate design modifications. Doing this by experiments is very time-consuming and expensive. Here, numerical simulations of the electric field distribution provide a highly useful tool. Unfortunately, however, it is not straightforward to translate the result from an *E*-field calculation into a statement whether a discharge or flashover will occur or not.

The basic mechanism behind the creation of a discharge is the ionization of the insulating gas [1]. An important quantity is the effective ionization α_{eff}, which is the rate of net production of free charges (electrons) in gas. It is equal to the ionization rate minus the recombination and attachment rates. Since the ionization rate is strongly dependent on the electric field E, so is α_{eff} (E) and the shape of this function varies depending on the gas.

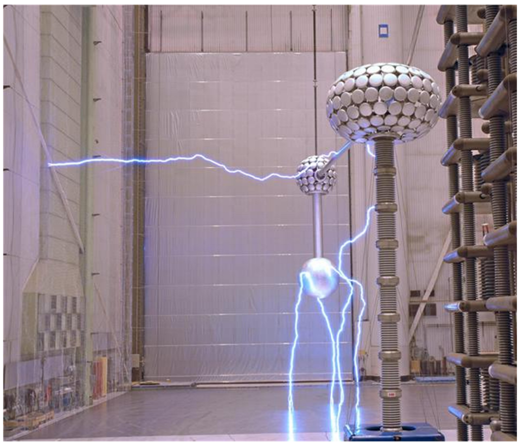

Figure 1. Very long discharges created with a high voltage test equipment.

Obviously, a necessary condition for the formation of a discharge is that $\alpha_{eff} > 0$ somewhere. This is, however, not sufficient since the primary electrons themselves will not lead to a macroscopically detectable discharge. For this to happen an electron avalanche must be formed, i.e. each primary electron accelerated in the electric field causes further ionization at an increasing rate. A self-sustained discharge, independent of charge injection from the electrodes, will form provided the total number of electrons becomes larger than some critical number. If we further assume that such an avalanche will extend in the direction of electron acceleration, i.e. along an electric field line, the condition for a self-sustained avalanche can be written [1,2]

$$S = \int \alpha_{eff}\,(E)\,dl > C_{crit} \tag{1}$$

where the integral is performed along the particular field line under consideration and only where α_{eff} $(E) > 0$. The critical number C_{crit} is usually taken to be in the range 15 - 20, let us say 18.4 in what follows The above criterion is called the streamer inception criterion. If it is fulfilled it guarantees the formation of a stationary streamer (or corona) discharge extending from the electrode, where usually

$\alpha_{eff}(E)$ has its maximum, out to the surface where $\alpha_{eff}(E) = 0$.

If $\alpha_{eff}(E) > 0$ along the entire field line, from the high voltage to the grounded electrode, the fulfillment of (1) will lead to an immediate breakdown across the gap. If, on the other hand, $\alpha_{eff}(E) < 0$ along parts of the field line there is still a chance for a complete flashover. This may happen if the electric field just in front of the streamer head is so high that the associated field ionization effectively moves the streamer head forward. This process, called streamer propagation, can take place provided the average field $\langle E \rangle$ along the field line satisfies [2]

$$\langle E \rangle = U/L > U_0/L + E_0. \tag{2}$$

Here U is the voltage difference between the electrodes, $L = \int dl$ is the length of the field line, $U_0 \approx$ 10-30 kV is an empirical constant, and $E_0 \approx$ 0.5 kV/mm for a discharge starting from the positive electrode and $E_0 \approx$ 1.2 kV/mm for a discharge starting from the negative electrode.

Here, we don´t consider leader propagation, where the hot plasma channel becomes so conductive that the field enhancement at the streamer head enables the streamer to propagate, more or less independently of the external field.

Although the computation of the background electrostatic field E is straightforward, the ability to evaluate the above-mentioned criteria has previously not been available in standard commercial field solver software. The challenge is to analyze a large number of field lines at the same time and to post process and visualize the result in an instructive way. Even in specialized in-house developed codes it has only been possible to analyze a limited number of field lines simultaneously.

In previous versions of COMSOL Multiphysics there has been no easily implemented method to perform the integrals along field lines, although it can in principle be done by formulating the problem in terms of an additional partial differential equation to be solved [3]. Using the Particle Tracing Module introduced in version 4.3 of COMSOL Multiphysics, such field line integrals can now be computed and analyzed in a more straightforward and efficient way. The implementation is simple and a large number of field lines can be evaluated simultaneously, both in 2D and 3D. Hopefully, this will result in a much faster and more reliable optimization process of insulation designs in high voltage equipment.

In the present contribution we describe the way to apply the massless particle tracing technique in order to compute the integrals, as well as an example of how the results can be presented in an intuitive manner. Some applications involving 2D and 3D geometries are provided.

2. Effective ionization function

Before proceeding to the solution procedure some words should be said about the effective ionization function $\alpha_{eff}(E)$. It behaves differently depending on the insulating gas. For air it can be approximated by a quadratic formula [4]:

$$\alpha_{eff}(E) = p\left[k\left(\frac{E}{p} - \Lambda\right)^2 - A\right]. \tag{3}$$

Here, k = 1.6 mm bar /kV^2, Λ = 2.2 kV/(mm bar), and 0.3 1/(mm bar). p is the pressure given in bar. $\alpha_{eff}(E) > 0$ for $E >$ 2.6 kV/mm, which therefore is the critical field strength needed for a net production of charge carriers to occur.

3. Solution procedure

3.1 General

The model includes two physical interfaces, viz. *Electrostatics* and *Charged Particle Tracing*, see Fig. 2. These are run separately, one after the other, in two different Studies. First, the *Electrostatics* problem is solved as a stationary problem in Study 1, providing the electrostatic background field. Then, the time dependent Charged Particle Tracing problem is run in Study 2, evaluating the streamer criteria integrals for each field line.

3.2 Electrostatic background field

For the purpose of demonstrating the procedure we use an axisymmetric model of a high voltage (105 kV) conductor penetrating an opening in a grounded wall. The hole is surrounded by a flange that complicates the field pattern and the solution. After running Study 1,

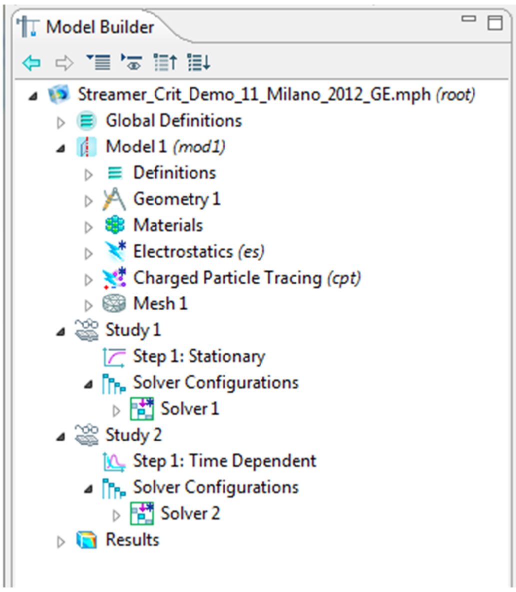

Figure 2. The general structure of the model displayed in the Model Builder.

the electric field is found as is shown in Fig. 3. Note the regions where E exceeds the critical value 2.6 kV/mm required for net charge production.

3.3 Particle Tracing

Once the background electric field is calculated we can turn to the evaluation of the streamer integrals. This is done by running the *Charged Particle Tracing* problem in Study 2. In this node we define the subnodes shown in Fig. 4.

The *Charged Particle Tracing* feature is originally intended for calculating trajectories of moving charged particles in electric and/or magnetic fields. However, electric field lines can be identified as the trajectories of charged particles having zero mass. Under the top node (*Charged Particle Tracing (cpt)*) one can in fact under the *Particle Properties* choose the *Massless* formulation.

The particle tracing procedure starts by selecting those surfaces from which the field lines are starting. This is done under the *Inlet* node. Also, the number of field lines ("particles") is entered. Preferably one selects all surfaces at either high or zero potential in order to make sure that all field lines are included in the analysis.

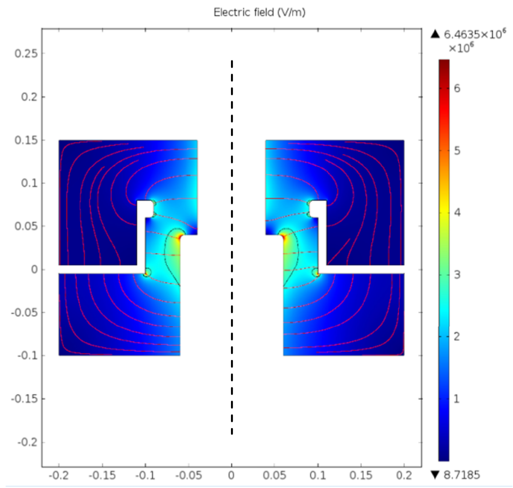

Figure 3. Electric field between high voltage conductor and grounded wall. Field lines in red and boundaries of regions where α_{eff} (E) > 0 are marked with grey curves.

The next step is to define the velocity of the "particles" under the *Particle Properties* node. If we want the particle trajectories to be identical to the field lines we should define the velocity as being parallel to **E**. Here it is convenient to use the normalized field in the definition of **v** according to $\mathbf{v} = \mathbf{E}/|\mathbf{E}|$, see Fig. 5. By using a velocity of the order of 1 m/s, and knowing the typical distances between positive and negative electrodes, one can easily estimate the time required for a "particle" to reach the opposite electrode. One also has to determine what happens to a "particle" once it reaches the opposite wall. Under the *Wall* node we choose the wall condition *Freeze* to make sure that the particle does not bounce back into the gas volume.

Under the *Charged Particle Tracing* node, we then define the required integrals along each field line. This is done by introducing *Auxiliary*

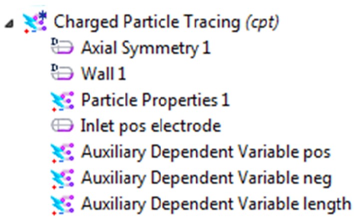

Figure 4. Definitions made in the *Charged Particle Tracing* node.

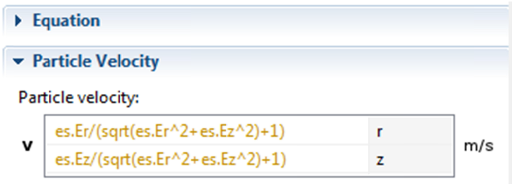

Figure 5. Definitions of the normalized velocity made in the *Particle Properties* node.

Dependent Variables, one for each integral we want to calculate, see Fig. 4.

The integrand is called *Source R* under the *Auxiliary Dependent Variables* heading. First, the field line length L is given by such an integral having R = 1. Then we define two different streamer integrals S given by (1): One for streamers emerging from the positive electrode and one for streamers starting at the negative electrode. For the integral corresponding to the positive electrode the integrand α_{eff} (E) is multiplied with a factor which is 1 when E decreases away from the positive electrode and 0 when E increases. The other integral is defined in an analogous way for the negative electrode. According to these definitions we can separate between streamers starting from either the positive or the negative electrode.

The final step consists of running Study 2 as a time dependent simulation, solving for the *Charged Particle Tracing* variables only, see Fig. 6. The integration is performed from t = 0 to some final time t = *t_end*. A reasonable value for *t_end* can easily be estimated as *t_end* = D/v, where D is the dimension of the object and v = $|\mathbf{v}|$ ~ 1 is the normalized velocity that is used.

4. Post processing

Now when we have the solution and the streamer integrals computed, it remains to present the result in an informative and easily understandable way.

First, the effective ionization function α_{eff} (E) corresponding to regions close to the two electrodes can be plotted. In Fig. 7 the area with a net electron production close to the positive electrode is shown while those close to the negative electrode can be seen in Fig. 8.

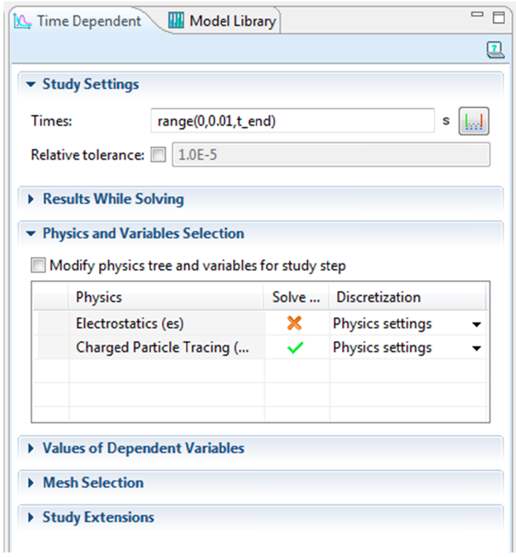

Figure 6. Settings for running the particle tracing time stepping in Study 2.

From Figures 7 and 8 we now know where the regions with net electron production are located and hence where we might expect discharges to be initiated.

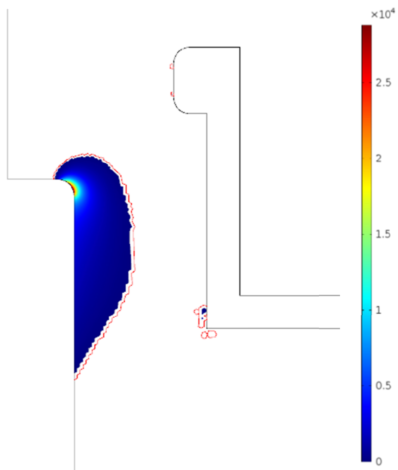

Figure 7. The region having a positive net electron production α_{eff} (E) > 0 close to the positive electrode.

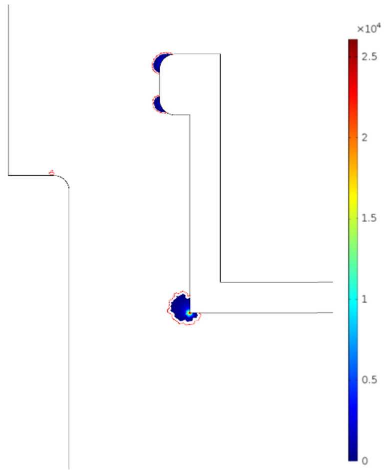

Figure 8. The regions having a positive net electron production α_{eff} $(E) > 0$ close to the negative electrode.

For this to happen, however, the criteria (1) for streamer inception has to be fulfilled. In addition, the criteria (2) must be satisfied if breakdown across the gap is to be expected.

Figure 9 shows the field lines that correspond to streamers starting from the positive electrode and satisfying (1). The magnitude of the integral S is color coded and the lines are only shown within the region having net charge production.

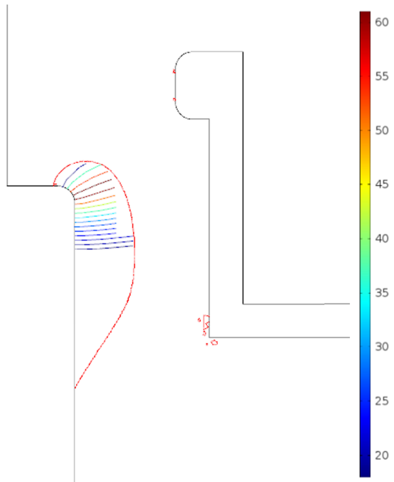

Figure 9. Field lines satisfying the streamer inception condition (1) for discharges starting from the positive electrode. Magnitude of streamer integral S is color coded.

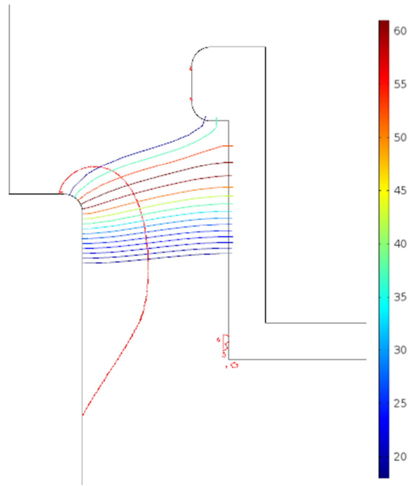

Figure 10. Field lines satisfying the streamer propagation condition (2) for discharges starting from the positive electrode.

It is interesting to observe that streamers are not initiated at all points on the electrode surface where the electric field exceeds the critical value 2.6 kV/mm. In Fig. 10 is shown the corresponding field lines which satisfy the condition (2) for breakdown across the gap. Note that in this case all field lines that satisfy (1) also fulfill (2). Finally, a similar pair of figures for discharges starting at the negative electrode can be seen in Figs. 11 and 12.

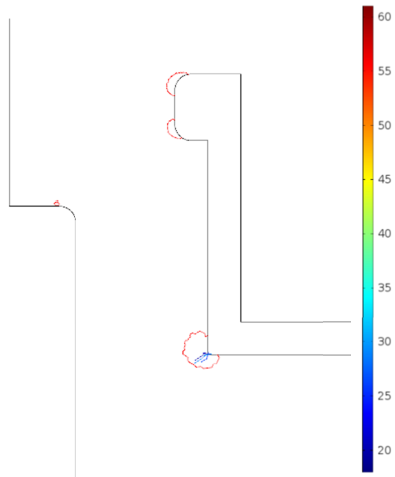

Figure 11. Field lines satisfying the streamer inception condition (1) for discharges starting from the negative electrode.

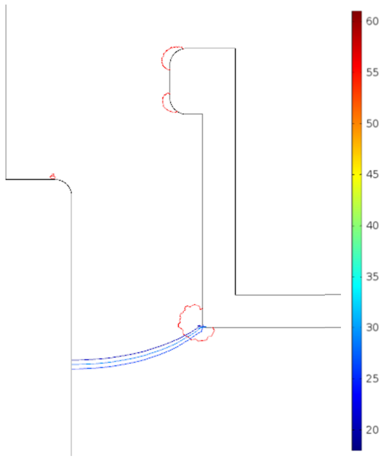

Figure 12. Field lines satisfying the streamer propagation condition (2) for discharges starting from the negative electrode.

5. A 3D example

As demonstrated above, the method works well in 2D. Below we also show that it can easily be applied to 3D geometries as well. To illustrate this we rotate the 2D geometry used above to generate a corresponding 3D model. Then, in order to introduce a truly three dimensional element, a block protruding from the inner high voltage conductor is added, see Fig. 13. The electric field is solved for and the particle tracing is carried out generating 1000 field lines to analyze as is seen in Fig. 14. Exactly the same post processing can be employed as for the 2D case shown earlier. As an example we display in Fig. 15 the field lines giving rise to a flashover from the positive to the negative electrode.

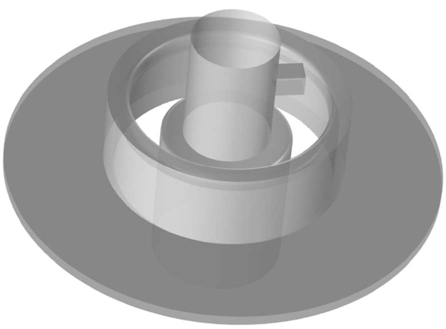

Figure 13. 3D geometry used in the simulation.

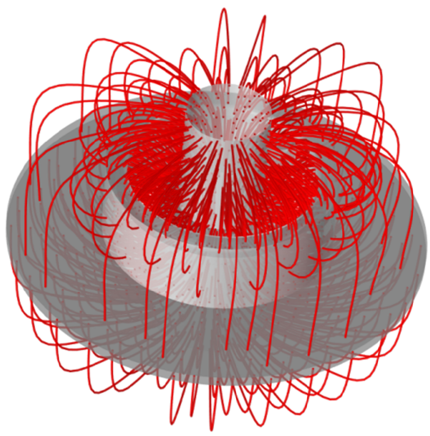

Figure 14. The 1000 field lines generated.

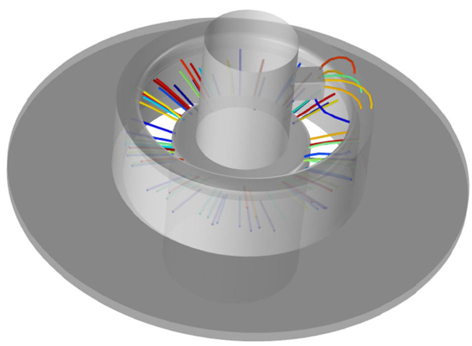

Figure 15. Field lines satisfying the streamer propagation condition (2) for discharges starting from the positive electrode.

Note the new flashover paths introduced from the protruding part of the high voltage electrode.

6. Conclusions

With the introduction of the Particle Tracing Module and in particular its ability to integrate arbitrary quantities along field lines, it has become possible to evaluate streamer discharge criteria in a relatively simple manner. From an engineering point of view this will have a significant impact on the design work on high voltage components, where the development of specialized in-house codes is no longer needed. As was demonstrated, the method works well in both 2D and 3D geometries.

7. References

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